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16. Abstract The background and development of an experimental 100 kW wind-energy generation system are described, and the results of current field tests are presented. The experimental wind turbine is a two-bladed down-wind horizontal axis propeller type with a 29.4 m diameter rotor and a tower 28 m in height. The plant was completed in March, 1983, and has been undergoing trouble-free tests since then. The present program calls for field tests during two years from fiscal 1983 to 1984. The development of technologies relating to the linkage and operation of wind-energy power generation system networks is planned along with the acquisition of basic data for the development of a large-scale wind energy power generation system.					
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DEVELOPMENT OF LARGE WIND ENERGY POWER GENERATION SYSTEM

Compressor and Plant Engineering Department*
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1. INTRODUCTION

*** / 543

Since 1973, oil crisis development of wind energy power generation has been promoted in various nations in the west as a national project in order to prepare for future energy diversification. Presently, in the west, proof tests for 100 kW wind energy power generators have been mostly completed, also a MW wind power generator is being tested, and their practical use is anticipated between 1990-2000. In our country, research for wind energy also has been done since around 1978. As a part of the Agency of Industrial Science and Technology in the Ministry of International Trade and Industry's "Sunshine Project", in 1981 the 100 kW wind energy power generation system development project was started with the goal of developing large scale wind energy generation systems in the future. This was the first step of this kind of development on a national scale specifically adapted to our country's natural conditions and energy situation.

This 100 kW wind energy experimental generator, designed and built by our company, was ordered by the Tokyo Electric Company through the New Comprehensive Energy Development Organization (1981). It was completed at Miyakejima Island, Tokyo, in 1982.

Proof tests were scheduled in 1983-1984. At present, through power output testing, various data relevant to wind energy power

* belongs to the main department of machinery
** belongs to the main department of technology
*** numbers in margin indicate pagination of foreign text

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Figure 1. General view of the experimental plant

production such as capacity, strength, vibration, etc. are being collected and analyzed, and we have been obtaining satisfying results compatible with our design projections.

2. DEVELOPMENT

2.1 Schedule for development of 100 kW wind energy generation system

The reason why we accepted the order for "Development of a Large Wind Energy Power Generation System", which was a part of "Sunshine Project", was that we had solved the basic problems of wind energy power generation such as aerodynamic capacity, vibrations and so on, and had established its design through research on 100 kW wind energy power generation two years before for the Tokyo Electric Power Company (1979). Research was started in 1979 by a project team of our company's Products Development Center and Technology Research Laboratory, and in two years vibration problems had been solved.

For the 1981 Sunshine Project (design and construction of an experimental 100 kW wind energy power generator), we were in charge of basic design of the total system, plus design and

TABLE 1. Schedule for development of 100 kW wind energy generation system

ITEM	YEAR							notes.
	1978	1979	1980	1981	1982	1983	1984	remarks
investigation, research								idea planning, wind tunnel test, theoretical analysis, etc
wind condition measurement								measured at Miyakejima Is. Tokyo
design								—
production, workshop test								—
installation								built at Miyakejima Is.
proof test								tested at Miyakejima Is.

construction of the nacelle and control systems with the help of subcontractors--Toshiba Electric Co., Sumitomo Metal Industry Co., Sumitomo Precision Machinery Industry Co. and Kawasaki Heavy Industry Co. During 1982, our company built the generator's main body and electrical instrumentation, and the Kanto Electric Construction Co. built the tower and other accessory equipment.

Since the development of wind energy power systems includes composite technology, from basic to applied technology, we organized a project team combining all the departments and tried to obtain the most comprehensive technological approach.

2.2 Points on technical development needing solution

/544

There are the following differences between wind energy turbine and the earlier steam or gas turbine:

- 1: no control over irregular wind energy input
- 2: spinning part has to be installed high on the tower
- 3: because of the small density of wind energy, the diameter of the blades becomes very great, and also the wind turbine is exposed to severe weather conditions.

In consideration of these characteristics, there will be the following points to be solved when developing a wind energy

generation system:

1. Considering our country's unique wind conditions, we need to establish a special design technique. In particular, we must consider our country's more changeable gusts and wind shear. These are greater than in western countries because of Japan's geographical situation.

2. Analyze the wind energy turbine's aerodynamic performance and dynamic load against wind changes, and analyze control-response of generator's energy output control, variable pitch control and yaw control.

3. Analyze vibration of the blades, tower, nacelle system, rotor shaft, etc.

4. Establish design parameters for blade's strength, structure and also technology for production. Establish operation know-how and safety system.

5. Research the power distribution and release systems, and noise effects to the environment.

6. Establish the best system with superior cost performance and economic and safe construction technology.

3. SYSTEM

3.1 Design

3.1.1 Fundamental condition

Basic conditions set for this experimental generator are as follows:

1. In order to fulfill the purpose of obtaining the basic data for future large scale wind energy power generation systems, mechanical construction must be reliable.

2. Being the first experimental generator and lacking operational data, a high priority must be set on system safety considering natural phenomena such as typhoons, earthquakes, lightning, etc., and abnormal conditions such as power break-

downs, machinery failures, etc.

3. It has to be designed matching the construction site's (Miyakejima Island) weather condition and environment, and also considering the transportation and construction methods according to the geographical condition.

4. In designing each system, method has to be clear, so later comparisons with tested measurement will be easy.

5. Use computers for control measurement system in order to be able to input different test conditions.

3.1.2 Essentials of design

Following are the design factors when considering the wind condition and environment of the construction site (Miyakejima Island).

3.1.2.1 Environmental condition

Essential points of designing according to the environmental conditions follow (designed to last 15 years):

1. Salt damage.

Solved by surface treatment (plating, coating, etc.) use of corrosion-resisting material and air tight construction.

2. Hail, dust proofing

Built to resist hail of 25mm diameter and blade surface coated with anti-erosion coating.

3. Sun light

Heat insulating material was installed inside the nacelle cover.

4. Earthquake

Built to conform with the new earthquake resistance standards for buildings. The tower in particular was built to stand up in three sympathetic vibration sine waves (input acceleration: 300 gal.).

5. Lightning

Installed a lightning rod on the nacelle and an alarm inside.

6. Typhoon

Conforming to the Building Standards Act, it was built to resist 68.2m/s wind at 28m high. Number of blades is two and they are feathered when it is not operating to avoid strong wind.

7. Noise

Kept the blade rotational speed as low as approximately 80m/s.

8. Wind condition

Designed considering gusts, wind shear, etc., according to wind condition data obtained from the measurement device previously installed.

3.1.2.2 Anti-vibration policy

In order to avoid sympathetic vibration, particular frequencies were assigned to the blades, nacelle (especially yaw system), tower and rotor shaft assembly. Also, the blades were designed very carefully not to cause destabilizing vibration such as flutter and divergence.

3.1.2.3 Generation control method

Since it is an experimental machine, the DC link method was employed, which little affects the power distribution system, and control generation output and can handle wind energy power generator solo operation.

3.1.2.4 Yaw control method

We adapted a self adjusting down-wind type in which the blades are installed on the lee side of the tower, so that the blades always catch the wind at a right angle. Yaw control was designed to detect the wind direction and orient the nacelle toward this direction using a hydraulic system.

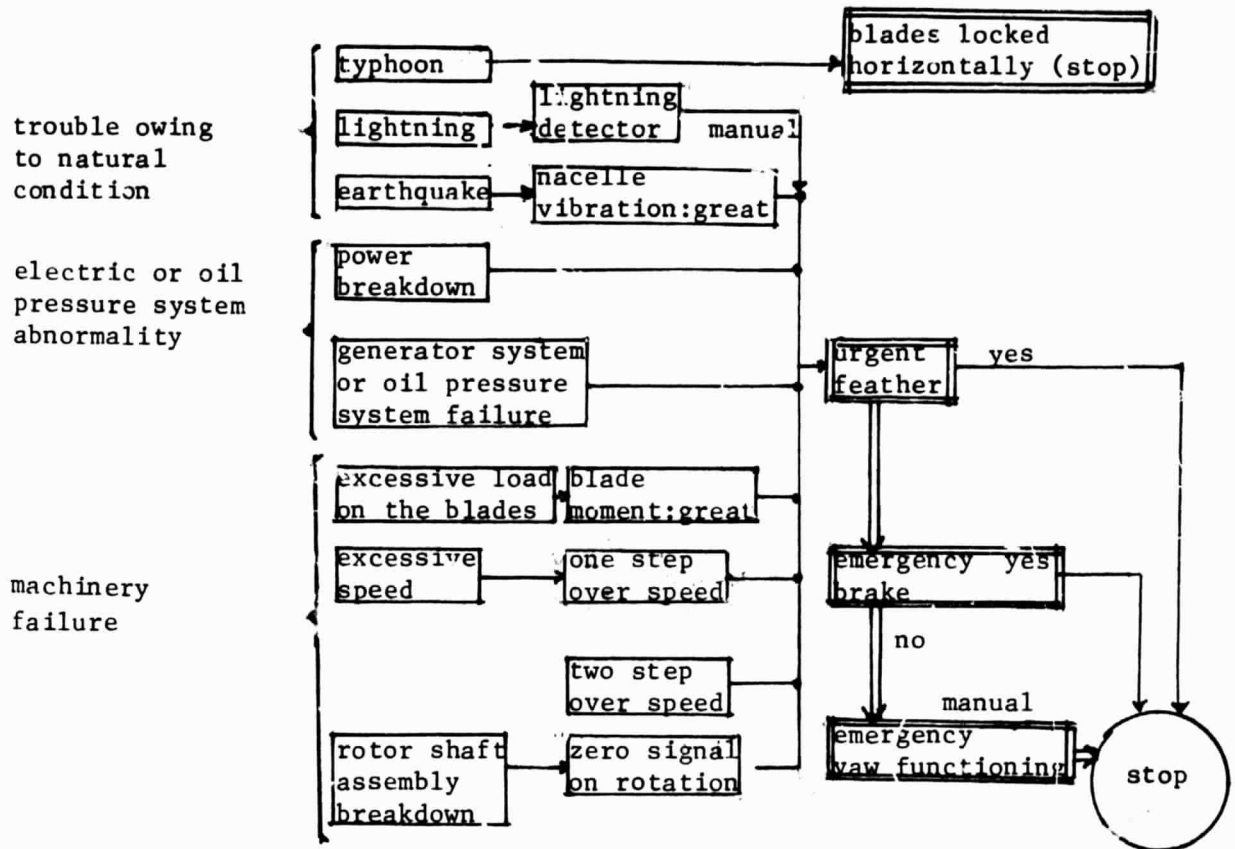


FIGURE 2. Countermeasures for abnormal conditions

3.1.2.5 Revolution and output control method

In order to simplify wind energy turbine control against wind velocity changes and to decrease the change of frequency, we employed a method of controlling the rotation fixed by generation output control and variable pitch control. Responsiveness of this control to wind velocity change is most important. We designed a control system which includes an oil pressure system after simulation analysis and other research.

3.1.2.6 Safety system and countermeasures for abnormal conditions

Considering the degree of urgency and importance of the effect on the system in case of emergency, the alarm system,

the ordinary stop, the urgent stop and the emergency brake stop were developed. In addition to a back-up system, a fail-safe type was adapted for stop control. For additional safety when stopped, a rotor lock device and feather lock device were supplied.

Countermeasures for the experimental generator failure is shown in Figure 2. Batteries were installed in case of control power breakdown and this contributes to safety control such as emergency stop control.

/545

3.2 Technical and structural data

3.2.1 Design specifications

Design specifications of this experimental generator are as follows:

<u>output</u>	<u>rated output</u>	<u>100 kW</u>
	wind condition	cut-in wind velocity approx 5m/s
		rated wind velocity 10m/s
		cut-out wind velocity 17m/s
		wind resistance (maximum instantaneous wind velocity) 68.2m/s
		(28m above ground)
<u>rotor</u>	<u>set-up</u>	<u>down-wind type</u>
	no. of blades	2
	diameter	29.4m
	rated rotation no.	51 rpm
	max rotational capability	61.2rpm
	rotation direction	counter clockwise (looking from windward)
	control system	variable pitch method
blade	length	12.5 (measured to flange)
	material	GFRP

<u>Tower</u>	<u>construction type</u>	<u>steel pipe truss</u>
	hub height	28m
<u>generation device</u>	generation method	DC link separately excited inverter
	generator method	alternating current synchronous method
	rating	100 kW
	revolution	1500 rpm
	frequency	50 Hz
	excitation	brushless indirect self-excited method
<u>operation control</u>	relative to wind direction	yaw control (oil pressure drive)
	relative to wind velocity	variable pitch (oil pressure drive)
	rotor control	fixed rotation control (combined with generation output control)
measurement system	data accumulation process	digital computer

3.2.2 System composition

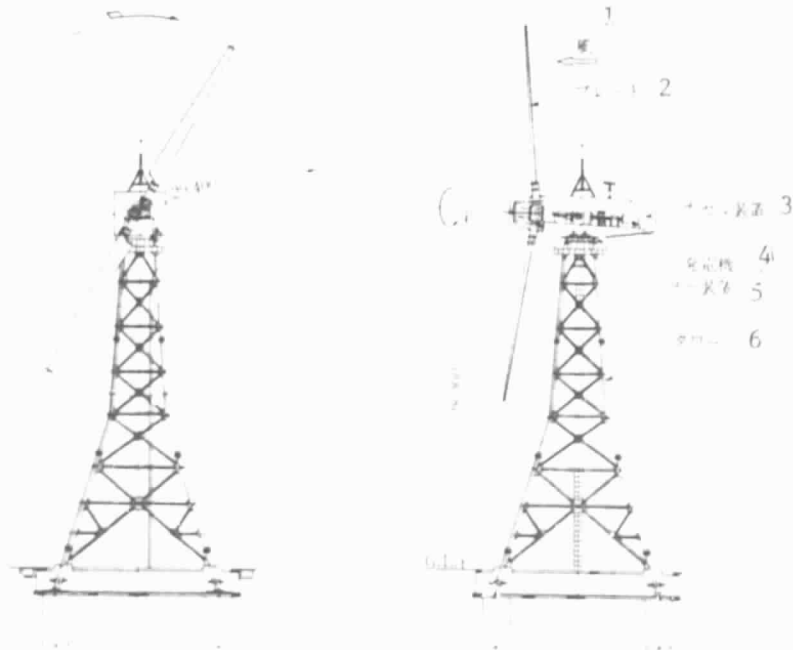
This experimental generator (Figure 3) is composed of blades, a variable pitch device, power transmission equipment, nacelle, a tower, a generator system (including generator), oil pressure devices, control devices, measurement devices, wind condition measurement devices and attachments (test tower, inside equipment, etc.) (Figure 4). First wind power is converted into mechanical rotation energy by the blades, and the rotation torque is transmitted to the generator through the bearing supported rotor shaft and accelerator. As described above, for safety reasons, the power transmission system is equipped with brakes and rotor lock device. The blades are made of GFRP for durability, light weight and are jam proof in regard to electrical waves.

By utilizing a variable pitch control system and a generator output control fixed rotation control is achieved. In this way, rotation is kept the same through the entire operating



第3圖 100 kW 風力發電實驗機

Fig. 3 Experimental 100 kW wind turbine generator installed



第4圖 100 kW 風力發電機組立圖 (單位: mm)

Fig. 4 General arrangement of experimental 100 kW wind turbine generator (unit: mm)

Key: 1--wind; 2--blade; 3--nacelle; 4--generator; 5--yaw device;
6--tower

wind speed range, and at the same time over-torque and excessive speeds during strong winds can be prevented. The variable pitch device is a link system and is driven and controlled by an oil pressure cylinder through a valve. The yaw device which controls the rotor is driven by an oil pressure motor to adjust to wind direction for efficient transmission of wind energy to the propeller. The systems installed on the tower such as the power transmission system, the variable pitch system, the yaw system, the cover, etc., are together called the nacelle system.

/546

The oil pressure system installed in the nacelle control the variable pitch and yaw, described above, but also brake and rotor inching control. The control system consists of these aforementioned wind turbine operational control and safety control systems--these systems are controlled electrically. The generation system is composed of (1) a generator, (2) a frequency alternator which at once converts the generated output to direct current and then reconverts it to the same alternating current and frequency as the power distributing system before sending power to the distributing system, (3) the output control system explained above.

The monitoring system of this experimental generator is divided as follows--measurement of wind conditions, capacity, load and vibration, oil pressure, pressure and temperature of lubricant and electrical system. Everything is automatically metered, monitored and analyzed by computers which consist of a detector, a monitor, a wind condition measurement device and data recording and display. Also this computer system is able to control the wind turbine.

Control and measurement systems are shown in Figure 5. Power generation systems except for the generator, control systems and measurement systems were installed inside the tower. The tower is a steel pipe truss structure which is designed to minimize the air turbulence (tower shadow). Also a three-person elevator

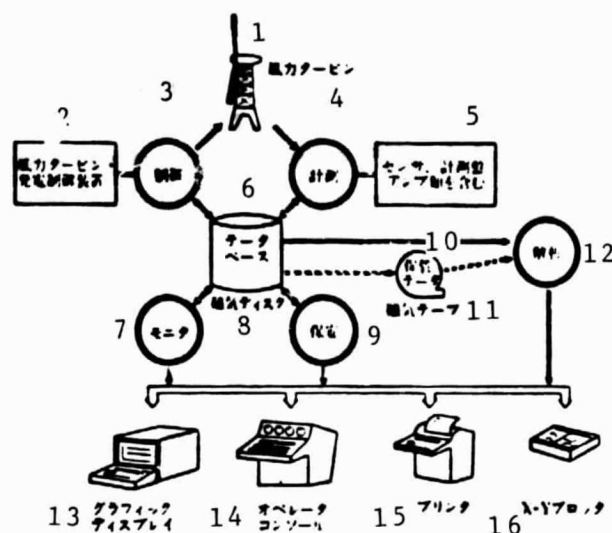


Figure 5. Flow chart of control and measurement systems

Key: 1--wind turbine; 2--wind turbine generation control system; 3--control; 4--measurement; 5--sensor, measurement disc (including amplifier); 6--data base; 7--monitor; 8--magnetic disc; 9--safety; 10--data deposit; 11--magnetic tape; 12--analysis; 13--graphic display; 14--operator console; 15--printer; 16--X-Y blotter

was installed. Inside are lighting equipment, an electrical distribution system, roads, security fencing and other appurtenances.

3.3 Operational capacity

3.3.1 Wind turbine performance

Figure 6 shows the wind turbine performance. The output factor varies relative to the rotation speed ratio and pitch angle of the blades. For performance analysis, strip theory was employed. On analyzing the influence of wind shear, tower shadow, etc., was considered.

Wind turbine performance varies relative to the shape of the blades. The effective operation range is limited by a counter

flow of the blades in a low wind velocity range, and by a speed loss characteristic of the blades in a high wind velocity range. An optimum blade shape was chosen after an integrated discussion and research considering performance and production conditions.

3.3.2 Operation and output characteristics against wind velocity

This experimental machine is operational at wind velocities between 5 and 17 m/s. It has been decided, for safety, economic and design reasons, that the wind turbine would be non-operational in the high wind velocity range of 17 m/s or higher (less than several percent a year). At a wind velocity of 4 m/s or higher, yaw control starts and the rotor is turned toward the wind direction. At a wind velocity of 5 m/s or less, the pitch angle of the blades is changed slowly from a feather condition of approximately 90° to 5°, and rotor revolutions are increased to the rated number. At velocities of 5--10 m/s electrical generation occurs with the pitch angle fixed at 5° while electrical output is controlled with generator rpm's staying at the rated 1500 rpm according to variations of wind velocity.

/547

At wind velocities between 10 and 17 m/s, output reaches the rated number and is maintained at 100 kW, in addition, the blade pitch angle is adjusted to keep the rated rotation at 1500 rpm. In order to avoid an increase of rpm relative to an increase in wind velocity, a variable pitch control is used to increase the pitch angle. At velocities of 17 m/s or higher, the pitch angle is turned to a feather condition of approximately 90°, while a backlashing torque is given to the wind turbine and it stops. Immediately after the rotor stops, the blades are kept in a horizontal position by the inching device and eventually by using brakes the rotor and nacelle are completely stopped.

For these instructions please refer to the dark arrow lines in Fig. 6. Characteristics of power outputs against wind velocity are shown in Fig. 7.

4. CONSTRUCTION

This experimental generator was built on a very windy coastal flat site on the Izu Peninsula, northwestern Miyakejima Island. Much discussion and research were necessary regarding the transportation and supply route of materials and machinery, environmental conditions, and so on, since it was built on an isolated island. By avoiding the typhoon season and getting much support from various sources, construction was completed with no accident, no disaster.

The best installation of such a wind energy power generator would employ large machinery to allow installation of the nacelle as a unit. However, it is often physically impossible on an isolated island to do so because of poor transportation, route and loading equipment. In this case, a relatively large truck crane was used, which was able to lift the nacelle frame and its common bed unit. Then, a temporary scaffolding having been built, various types of machinery for the nacelle interior and the blades were assembled and installed.

5. TEST

5.1 Workshop test

Prior to the actual installation, separate functional tests for the nacelle system, the generation system and the control measurement system were completed at our company's second Tokyo factory (Figure 8). The tests showed that each system met design standards for performance. The nacelle and oil pressure systems were assembled on a temporary bend and the following tests were done--vibration test for the blades and nacelle, rotation and vibration test for the rotor shaft, measurement of lost torque of the rotor system, measurement of time constant of the variable pitch system and performance of other instruments. Table 2 shows the results of these testings.

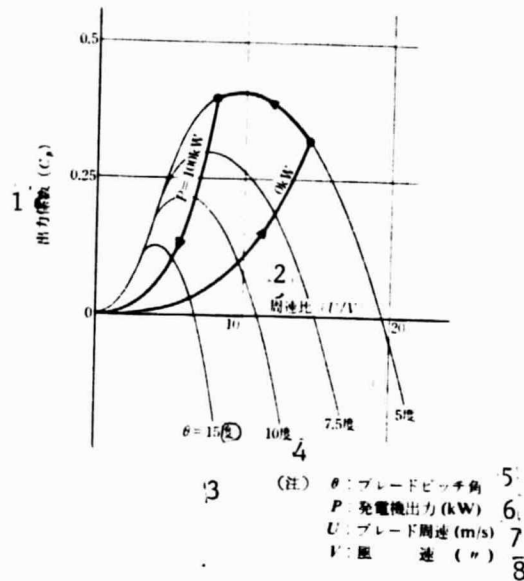


Figure 6. Characteristics of wind turbine performance

Key: 1--output factor; 2--rotation speed ratio; 3--degree; 4--notes; 5--blade pitch angle; 6--generator output; 7--blade rotation speed; 8--wind velocity

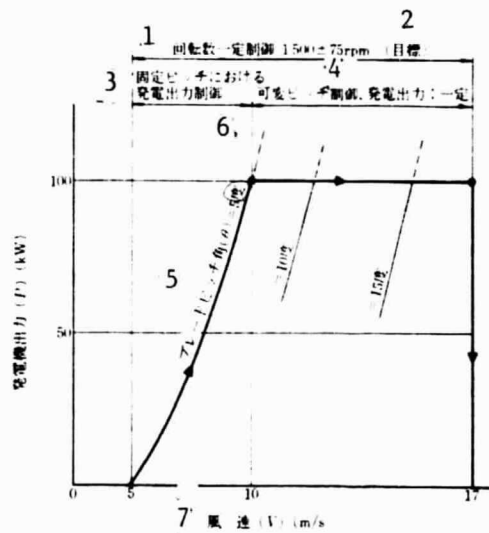


Figure 7. Characteristics of power output

Key: 1--fixed rotation control; 2--aim; 3--generation output control at fixed pitch; 4--variable pitch control, generating output; 5--fixed; 6--degree; 7--wind velocity

TABLE 2. Workshop test results

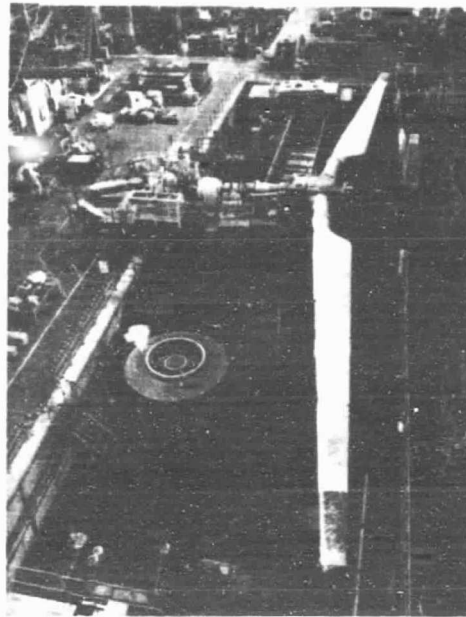
7 項目	8 試験結果	9 標準値
1 分類		
2 ブレード振動試験	ブレード停止中の1次固有振動数(測定値)は2.0Hzであった 10	2.1 Hz 以上 15
3 ナセル振動試験	ロー（水平面内）の1次固有振動数(測定値)は2.5 Hzであった 11	2.0 Hz 以上 16
4 ロータ軸回転および振動試験	運転時に監視範囲(定格の120%まで)において、軸系のねじり・曲げ振動とも異常はなかった 12	—
5 可変ピッチ時定数測定試験	ブレードの回転停止中、可変ピッチ系の時定数(測定値)は0.11~0.17sであった 13	0.2s 以下 17
6 機器作動確認試験	可変ピッチ、フェザーロック、ロータロック、インチング、ロー（各動作）とも正常に作動し、所定の仕様をみたしていた 14	—

Key: 1--classification; 2--blade vibration test; 3--nacelle vibration test; 4--rotor shaft rotation and vibration test; 5--variable pitch time constant measurement test; 6--machinery performance confirmation test; 7--items; 8--test results; 9--standard value; 10--first intrinsic number of vibration (measurement result) when the blades were stopped was 2.0Hz; 11--first intrinsic number of vibration of yaw structure (horizontal) was 2.5Hz (measurement); 12--no abnormal twist or vibration in the shaft in rotation range (up to 120% of the rating); 13--time constant (measurement) of variable pitch system when the blades were stopped was 0.11-0.17s; 14--variable pitch, feather lock, rotor lock, inching, yaw (each movement) all functioned normally; 15--around 2.1 Hz; 16--2.0 Hz or up; 17--0.2s or less

5.2 Adjustment test on the scene

In 1982, after the installation of this experimental generator at Miyakejima Island, the following tests were done: a particular tower intrinsic vibration measurement test, machinery function adjustment tests and rotation start confirmation adjustment tests. The result of an actual measurement of the intrinsic vibration of the tower (first) was 2.44 Hz which fulfilled the standard value 2.2 Hz or greater. Also the safety system and other machinery functioned normally, and it was confirmed that the wind turbine started and stopped without incident in a natural environment (wind of 4 m/s or greater). In the end, voltage

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Figure 8. Workshop test

proof tests for 6600 V high voltage power distributor and 440 V generator system were done and completed the whole construction process.

5.3 Actual proof test

In 1983, we started actual proof tests at Miyakejima Island. At present, we are collecting test data and a detailed analysis is in process. Since this project is a part of "Sunshine Project", details of this year's test results are not included. This experimental generator has approached the rated power output, has been producing satisfying results, and is undergoing continued testing without trouble. The good results were made in capacity, control, strength and vibration.

Following the 1983 tests, which determined the characteristics of capacity, strength and vibration by solo operation of consuming output with a resistor, in 1984 we are planning to determine characteristics when systems are linked with a power distribution system.

6. CLOSING REMARKS

The 100 kW wind energy power generator which was built in March 1983 at Miyakejima Island, Tokyo, as a part of the "Sunshine Project" (Sunshine Project Promotion Center, Agency of Industrial Science and Technology in the Ministry of International Trade and Industry) is the first experimental generator made with the goal of actual development of large scale wind energy power generation systems in our country. Actual proof tests are being done 1983-1984. So far, according to the test results, there is no problem with machinery or control.

Performance is expected to be satisfactory as well. As far as practical use of wind energy power is concerned, there are many problems to be solved such as safety, liability, adjustment to the environment, finance and so on. However, with these test results we are continuing our research and development for utilization of wind energy power generation systems.

In conclusion, we very much appreciate the support from the New Energy Development Organization and the Tokyo Electric Power Company.

by Kenji Ohmae
Fumiaki Sano